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Physical Work and Cognitive Function
During Acute Heat Exposure
before and after Heat Acclimation

Mark J. Patterson, Nigel A.S. Taylor
and Denys Amos

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Physical Work and Cognitive Function During Acute Heat Exposure Before and After Heat Acclimation

Mark J. Patterson, Nigel A.S. Taylor and Denys Amos

**Combatant Protection and Nutrition Branch
Aeronautical and Maritime Research Laboratory**

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ABSTRACT

Eight physically active males, without a history of heat acclimation were studied during heat exposure for 22 consecutive days. Physiological adaptation and cognitive function were evaluated during heat stress tests. Four cognitive function tests were administered at intervals during the study. These tests involved assessment of perceptual function, spatial orientation, temporal orientation and vigilance. The observations show that heat acclimation improves the capacity to perform physical work in the heat. However, neither unfamiliar nor habitual heat strain appear to induce attentional disturbances, temporal or spatial disorientation, or altered visual perception, as quantified within this experimental design. While these data indicate that cognitive function is not affected by heat, it is possible that the cognitive function tests used were not sufficiently sensitive to quantify heat-induced impairment. It is also possible that changes may only appear in more complex cognitive tasks.

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Physical Work and Cognitive Function During Acute Heat Exposure Before and After Heat Acclimation

Executive Summary

The combination of prolonged exercise and heat exposure, such as encountered during military operations in Northern Australia, redistributes blood flow to exercising muscles to satisfy metabolic demands, and to the skin to dissipate heat. Most people can meet this demand. However, during prolonged exercise in the heat, even highly trained individuals may fail to maintain thermal equilibrium and will move into positive heat storage. In such situations, both physical and mental performance have been shown to be impaired. While the changes to physiological function are well known, the effects of acute heat exposure on cognitive function are uncertain.

While there is some evidence that the thermal environment does impact on cognitive, perceptual and motor functions, the evidence is not unambiguous. A lack of consistency in the measurement of thermal stress and strain in many investigations restricts the value of such work. However, it appears that heat stress, under certain circumstances, may impact on some forms of cognitive and motor performance. The present study sought to confirm this interpretation using four cognitive-function tests. Thermal strain was achieved by the combination of thermal environment and exercise. This strain was held for at least one hour prior to test administration and a minimum strain of at least 38°C (body core temperature) was imposed on the test subjects.

The results indicated that high levels of thermal strain, combined with exercise, did not impair visual attention, temporal or spatial orientation, or visual perception. It might be argued that other tasks may be more appropriate for use in military operations. The limitation of using more complex tasks is that the results may become difficult to interpret. While the present data show that, on function-specific tests, separate cognitive functions appear to be neither impaired by heat strain nor restored following heat acclimation, they tell us nothing about the impact on more complex tasks. It may be that cognitive performance becomes affected by heat strain only within complex tasks or indeed that heat strain has no effect on cognitive function.

Given the equivocal nature of the evidence within the literature, it is recommended that a thorough re-assessment of the impact of thermal strain on simple cognitive function be investigated. It is further recommended that complex cognitive function tasks or task simulations be developed and the impact of thermal stress upon such tasks be assessed. Such complex tasks should be performed using realistic simulations, including auditory and visual distractions.

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1. Introduction

During exercise, a person weighing 70 kg and performing work at a rate of 200 J.s^{-1} , in a thermo-neutral environment, would consume oxygen at approximately 2.5 L.min^{-1} , and experience a total metabolic energy use of approximately 1000 J.s^{-1} . About 800 J.s^{-1} of this energy would be converted to heat energy. Since a storage of about 3.5 kJ of heat per kilogram body mass causes tissue temperature to rise 1°C (mean specific heat of tissues), then heat storage at a rate of 800 J.s^{-1} (48 kJ min^{-1} , assuming zero heat dissipation), would cause tissue temperature to rise by 1°C in just over 5 minutes. If we assume a pre-exercise mean body temperature of 36°C , and a maximal upper limit of 41°C , then our person would reach this point in 25.5 minutes. Yet, people frequently exercise for several hours at this work rate without suffering the symptoms of hyperthermia. This is possible primarily because of our well-developed evaporative cooling mechanism. However, even when the person maintains thermal homeostasis, there may be a cost to both physiological and cognitive functions.

The combination of prolonged exercise and heat exposure forces the cardiovascular system to provide blood flow to skeletal muscles to satisfy metabolic demands, and blood flow to the skin to dissipate the heat released from the exercising muscles. Most people can meet this dual demand, at least for a short duration. However, during prolonged exercise in the heat, even highly trained individuals may fail to maintain thermal homeostasis, and will move into positive heat storage. In such situations, both physical and mental performance have been shown to be impaired (Epstein, *et al.*, 1980; Nunneley *et al.*, 1982). While the changes to physiological function are well known (Bean and Eichna, 1943; Greenleaf and Greenleaf, 1970; Wyndham, 1973; Sciaraffa *et al.*, 1980; Rowell, 1983), the effects of acute heat exposure upon cognitive function are less certain. We have recently reviewed the literature regarding this topic (Patterson, Taylor and Amos, 1997), a summary of which is contained in Table 1.

A considerable amount of the human factors research in this area has been undertaken by either physiologists, with a limited appreciation of the assessment of cognitive performance, or by psychologists, with a limited understanding of the physiological impact of the thermal environment. As a consequence, the literature is diluted by numerous poorly controlled experiments, and therefore is difficult to interpret. One of the major limitations of such research has been a failure to define adequately the thermal environment and the resultant thermal strain, as evidenced by core temperature (T_c). Furthermore, some investigators have observed divergent results at a similar T_c . In such cases, the T_c may have been similar, but the air or skin temperatures were changing. The present study was designed to overcome this limitation.

Table 1. Literature summary: effects of heat stress on cognitive function.

Authors	Function	Conditions	Observation
Mackworth, 1950	vigilance	T_a 21, 26, 31, 36°C	↓ above 26°C
Benor & Shvartz, 1971	auditory vigilance	T_a 50°C	↓ with rising T_c
Epstein <i>et al.</i> , 1980	reaction time	range of ET	↑ above 35°C
Colquhoun, 1969	reaction time	ET 27.8-33.3°C	no change
Epstein <i>et al.</i> , 1980	target shooting	range of T_a	↓ with rising T_a
Holland <i>et al.</i> , 1985	memory	range of T_a	no change
Bunnell & Horvath, 1988	memory, reasoning, visual searching, divided attention, spatial orientation	range of T_a	no change
Nunneley <i>et al.</i> , 1982	spatial orientation	range of T_c	no change
Fox <i>et al.</i> , 1967	time orientation	vapour-barrier suit with ↑ T_c	↓ with rising T_c

Notes: T_a = ambient temperature; ↓ = decreased or elevated state; ↑ = increased or elevated state; T_b = mean body temperature (weighted sum of core and skin temperatures); ET = effective temperature; T_c = core temperature.

While there is some clear evidence that the thermal environment does impact upon cognitive, perceptual or motor functions, this evidence is not unequivocal. The lack of consistency in the quantification of the thermal stress and strain in many investigations restricts the value of such work. Similarly, differences in both task duration and complexity may confound data interpretation. However, on the basis of the evidence reviewed (Patterson *et al.*, 1997), it appears that heat stress, under certain circumstances, may impact upon some forms of cognitive and motor performance. These influences may be apparent within: sustained attention (vigilance); reaction time; spatial and time orientation.

The current study sought to confirm this interpretation using four cognitive-function tests, within the following design: (i) thermal strain was achieved by the combination of the thermal environment and exercise; (ii) the strain was held for at least 1 hour prior to test administration; and (iii) a strain (T_c) of at least 38°C was imposed on all test subjects.

2. Methods

2.1 Subjects

Eight healthy, physically active males (Table 2), without a history of heat acclimation, were tested during the months August-October (Southern Hemisphere winter-spring), to minimise seasonal acclimatisation effects, at the University of Wollongong¹. During this time, the average daily maximum and minimum temperatures were 20.5°C (S.D. 4.4)² and 10.3°C (S.D. 3.3). Each person was in good health and asymptomatic for cardiovascular dysfunction. Subjects were studied for 22 consecutive days, including 19 days of heat exposure within a climate-controlled chamber. All procedures were approved by the Human Research Ethics Committee, University of Wollongong, and all subjects provided informed consent.

Table 2. Characteristics of subjects.

Subject	Age (y)	Mass (kg) Day 1	Mass (kg) Day 8	Mass (kg) Day 22	Height (m)	V _{O2peak} (L. min ⁻¹) Day 0
S1	20	66.3	66.6	65.2	1.79	4.179
S2	20	85.1	84.9	85.8	1.97	6.694
S3	18	85.8	83.6	83.6	1.82	3.817
S4	24	76.1	77.3	76.9	1.81	4.549
S5	20	75.5	74.8	75.0	1.84	4.254
S6	19	59.1	59.2	59.5	1.70	3.332
S7	28	84.2	83.8	81.4	1.80	3.815
S8	24	87.9	89.2	88.1	1.89	-
Mean	22	77.5	77.4	77.0	1.83	4.377
S.D.	3	10.4	10.2	10.1	0.08	1.093

Abbreviations: V_{O2peak} = peak oxygen uptake (aerobic power) measured during an incremental, semi-recumbent cycle protocol.

¹ Latitude: 34.41° South, longitude 150.88° East, altitude 30 metres.

² Data are presented as means with either standard deviations (S.D.) or standard errors of the mean (±).

2.2 Procedural overview

Heat stress tests (HST:130 minutes) and acclimation trials (90 minutes) were all undertaken at an air temperature (T_a) of 39.8°C (S.D. 0.5), with relative humidity controlled at 59.2% (S.D. 0.8). In all cases, wind speed was less than 0.5 m.s⁻¹, and black globe temperature was within 0.5°C of T_a . Since this project was undertaken as part of a larger investigation, in which physiological testing was performed within heat stress tests (HST) on Days 1, 8 and 22, cognitive-function tests were completed on Days 1, 2 and 20 of the protocol (Table 3). Days 7, 14 and 21 were non-exposure, rest days, and Days 6 and 19 were combined peak aerobic power testing and heat-acclimation days, where heat exposure immediately followed the power test, but was shortened to 60 minutes.

Two days prior to commencing heat exposure (Day 0), subjects performed peak aerobic power tests in an air-conditioned laboratory (20°C). Each test involved semi-recumbent cycling to volitional exhaustion (Quinton Excalibur ergometer, Quinton Instrument Company, U.S.A.), with expired gases collected and analysed to derive peak oxygen consumption ($V_{O_{2peak}}$)³, using an automated gas analysis system (2900 Sensormedics, U.S.A.). Data from these tests were used to determine work rates for both the HSTs, and the combined exercise and heat acclimation exposures.

2.2.1 Experimental standardisation

Subjects were thoroughly informed concerning their daily and pre-experimental requirements. Accordingly, subjects refrained from strenuous exercise and consumption of alcohol or caffeine 24 hr prior to each stress test. Fluid and food intakes for 24 hours prior to each HST were closely prescribed, to ensure uniform carbohydrate intake and euhydration. All HSTs and cognitive-function tests were conducted at the same time of day. Subjects wore only cycle pants or swimming costumes, and open-toed sandals throughout both the HSTs and the acclimation regimen.

2.3 Heat acclimation protocol

The heat-acclimation regimen commenced the day after the first HST, and incorporated two distinct phases.

(i) *Phase I: Heat stress tests (Days 1, 8 and 22)*: Each HST involved both rest and exercise in the heat. Subjects commenced this trial resting (semi-recumbent) in the climate chamber at 28°C (60% relative humidity). During this phase subject preparation was completed. The chamber temperature was then elevated, over 20 minutes, to its target temperature (40°C) and relative humidity (60%). The subjects then started a 30 minute resting heat exposure, followed by three 30 minute stages

³ Peak aerobic power is reported in absolute units (L.min⁻¹) since the exercise performed was semi-recumbent cycling, and body mass was fully supported throughout exercise.

of semi-recumbent cycling (Quinton Excalibur ergometer, Quinton Instrument Company, U.S.A.). These work rates were designed to elicit a controlled elevation in body core temperature to 39°C.

- (i) *Stage 1*: Day 1: 30% peak work rate (110.4 watts averaged across subjects); Day 8: 30% peak work rate (110.4 watts); Day 22: 30% peak work rate (114.9 watts).
- (ii) *Stage 2*: Day 1: 28.9% peak work rate (104.1 watts); Day 8: 28.9% peak work rate (104.1 watts); Day 22: 28.9% peak work rate (108.4 watts).
- (iii) *Stage 3*: Day 1: 27.5% peak work rate (97.8 watts); Day 8: 27.5% peak work rate (97.8 watts); Day 22: 28.4% peak work rate (101.2 watts).

After 90 minutes, the work rate was elevated in a ramp function (4% peak power per minute: 14.5 ± 5.1 watts.min⁻¹) till the subjects reached volitional exhaustion, T_c reached the pre-determined upper cut-off point (39.5°C), or cardiac frequency (f_c) increased to 95% of the f_c reserve. Fluid replacement was not permitted until the HST was completed, whereupon an iso-osmotic fluid, approximately equal in mass to the mass change of the subject during the HST, was consumed under supervision.

- (ii) *Phase II: 16 heat-acclimation days*: During these exposures (Table 3), subjects cycled upright (Monark 868 ergometer, Sweden) for 90 minutes. Each session started with 30 minutes cycling to elevate T_c to 38.5°C. On the first heat-acclimation day (Day 2), the mean work rate was 162.9 watts (S.D. 71.6), while on the last heat-acclimation day (Day 20), it was 168.8 watts (S.D. 68.2). During the remaining 60 minutes of each exposure, subjects continued cycling, but external work rate was adjusted to maintain, or slightly elevate T_c (Regan *et al.*, 1996).

Subjects were provided with water at 30 minutes (200 mL) and 60 minutes (200 mL) during each acclimation exposure, and then with iso-osmotic drinks at the conclusion of each acclimation session, to replace mass loss.

Table 3. Details of daily heat-acclimation protocol.

Heat-acclimation day	Protocol summary
1	heat stress day
2	acclimation day - cognitive function tests
3	acclimation day
4	acclimation day
5	acclimation day
6	peak aerobic power + acclimation
7	rest day: no heat exposure
8	heat stress day
9	acclimation day
10	acclimation day
11	acclimation day
12	acclimation day
13	acclimation day
14	rest day: no heat exposure
15	acclimation day
16	acclimation day
17	acclimation day
18	acclimation day
19	peak aerobic power + acclimation
20	acclimation day - cognitive function tests
21	rest day: no heat exposure
22	heat stress day

2.4 Assessment of physiological function

Body core temperature (T_c) was recorded from the auditory canal (T_{ac}) and rectum during cognitive function testing. During HSTs, T_c was also measured from the oesophagus (T_{es}). T_{ac} was measured using an insulated, moulded earplug and aural thermistor (Edale Instruments Ltd, U.K.). While T_{ac} is influenced by environmental conditions, this effect is minimised by insulating the thermistor, and by using a T_a close to T_c . When these conditions are satisfied, T_{ac} and tympanic temperatures faithfully track oesophageal temperature (Cotter *et al.*, 1995). Thus, dampening effects, sometimes seen with T_{ac} , are negated within the current experimental design, in which subjects acted as their own controls, and in which the environmental conditions were equivalent between trials. Rectal temperature (T_{re}) was measured using a thermistor (YSI probe no. 401, Yellow Springs Instrument Co., Ohio, U.S.A.), positioned 12 cm beyond the anal sphincter.

Body mass changes were determined (A&D electronic balance, Model No. fw-150k, U.S.A.), corrected for fluid consumption, but not metabolic or respiratory losses and provided a gross estimate of total sweat activity. Cardiac frequency (f_c) was monitored from ventricular depolarisation, logged at 0.2 Hz (Polar Electro Sports Tester, model PE4000, Finland).

Physical work capacity in the heat was assessed during each of the three HST trials (*i.e.* Days 1, 8 and 22; see Section 2.3). Work capacity was evaluated in three ways. First, the total work completed (kJ) during the first 90 minutes of the HST was derived. This varied as a function of changes in V_{O2peak} for each subject. Second, the total work performed (kJ) during the incremental exercise stage, at the end of the 90-minutes cycle period, was calculated. Finally, these two work assessments were summed to determine the total work completed (kJ) during each HST.

2.5 Assessment of cognitive function

Four cognitive-function tests were performed on three separate days (Appendix One). These tests were chosen on the basis of the test selection criteria, and the recommendations of Patterson *et al* (1997; Sections 2 and 4).

Prior to heat exposure, subjects were exposed to a standardised familiarisation and learning procedure, for each of the four tests employed. Two baseline tests were performed to provide both basal data, and to ensure that task learning was complete. On Day 2 of acclimation (Table 3), subjects performed the first experimental battery of cognitive-function tests, while exercising in the heat. These tests were administered between 80-90 minutes of the combined exercise and thermal exposure. Data from this day enabled an assessment of the effects of acute, and unfamiliar heat exposure upon cognitive function. The fourth set of cognitive-function tests was completed on Day 20. This test battery was administered at the same time of day for each subject, and at the

same point within the exercise and thermal exposure. Accordingly, these tests were performed at the same relative exercise intensity between Days 2 and 20. It was hypothesised that an unfamiliar heat exposure would impair cognitive function. Therefore, this last test battery was administered to evaluate the possibility that repeated heat exposure may minimise the possible impact of heat stress on cognitive function.

The pre-exposure tests were performed with subjects sitting quietly within an air-conditioned laboratory. When the test batteries were performed in the heat, thermal stress was induced using a combined exercise and external thermal loading, and each test was performed while subjects continued cycling. Tests were completed within the last 10 minutes of each 90 minutes exposure.

2.5.1 Visual inattention

Perceptual function was assessed using the line-bisection task developed by Schenkenberg *et al.* (1980). This test specifically deals with the visual inattention phenomenon (visual extinction or visual neglect), and relates to the absence of awareness of visual stimuli which occur in the left field of vision. Visual inattention is, therefore, associated with right hemisphere dysfunction. Since it is the right hemisphere which dominates in the processing of visual information, and generally dominates the attention domain, a loss of visual acuity in the left field of vision corresponds with reduced visual attention.

Test summary: Subjects were presented with 20 lines of different lengths, some of which crossed the mid-line of the page. Six of these lines were located to the left of the mid-line, six were centred, and six were positioned to the right of the mid-line. The top and bottom lines were always centred. The subject was asked to: "cut each line in half by placing a small line through each line, as close as possible to the centre". The non-drawing hand was kept off the table. Only one mark was made per line. No lines were skipped, and all lines were marked in sequence. A different sheet was used for each trial. No time limit was imposed, and subjects were asked to complete the entire presentation sheet. The score obtained represented the percentage deviation, and quantified the extent to which the subject failed to correctly estimate the true centre of each line ($\text{percent deviation} = [\text{measured left half} - \text{true half}] / \text{true half} * 100$). Positive scores recorded when the right hand was used are indicative of visual inattention.

2.5.2 Spatial and temporal orientation

A perception of oneself in relation to the surrounding environment, objects within that environment, and events occurring within that environment (*i.e.* orientation) requires consistent and dependable integration of attention, perception and memory. This strong reliance upon various processes makes orientation vulnerable to the effects of

brain dysfunction, and tests of this function may be well suited to testing the effects of thermal strain. Two orientation tests were employed: spatial and temporal orientation.

Test summary: spatial orientation. Subjects were asked to mentally re-orientate figures of men (manikins) holding a black disk in one hand. The manikins had four standing positions: facing forwards, facing backwards, standing upright, standing upside down. Each position was shown four times with black disks being equally distributed between the two hands. Subjects indicated which hand was holding the black disk (Ratcliff, 1979). All subjects achieved maximum scores during the first cognitive-function test conducted in the heat. Consequently, this test was not reassessed on Day 20 of the protocol.

Test summary: temporal orientation. Subjects estimated the passage of selected time intervals after Benton *et al.* (1964). Five measures of time were utilised: date, day, time, time since exercise commenced, and time since cognitive-function tests commenced.

2.5.3 Sustained attention or vigilance

Attentional deficits are manifest as a reduced ability to focus on a given task. Such deficits may be induced by attentional disturbances, which can be simply identified in sustained attention tasks (vigilance).

Test summary: Subjects were presented with a sheet of paper containing 416 letters (16 rows of 26 lower- and upper-case letters). On each row, these letters were interspersed with ten capital letters and four double spaces. Subjects were asked to mark all upper-case letters and all lower-case letters following a double space (excluding margins) using a single line. However, upper-case letters which proceeded a double space were marked with a cross. Subjects were given 60 s to complete as many rows as possible. Two attempts were administered within each trial. Subsequent attempts and trials used different presentation sheets for each subject. Scoring was based upon errors and omissions (Talland and Schwab, 1964).

2.6 Psychophysical indices

Three psychophysical indices of strain were employed: thermal sensation; thermal discomfort; and perceived exertion. These tests were administered during the three HST trials (*i.e.* Days 1, 8 and 22; see Section 2.3). Thermal sensation and discomfort were assessed prior to the HST exposure (0 minutes), during seated rest (15 minutes), at 30, 60 and 90 minutes (after exercise started), and then at the end of maximal exercise. Effort sense was evaluated only at times where exercise was being performed. Instructions for the use of all scales were read to each subject prior to commencing each trial, and, for familiarisation purposes, a sheet containing full instructions and each rating scale was provided to each subject (Appendix Two).

Thermal sensation was obtained using a 13-point scale (modified after: Gagge *et al.*, 1967). The scale has numbers ranging from 1 (unbearably cold), to 7 (a neutral sensation), and finally to 13 (unbearably hot). Subjects responded to the question: "How does the temperature of your body feel?". Thermal discomfort was recorded in response to the question: "How comfortable do you feel with the temperature of your body?". Subjects responded using a scale with numbers ranging from 1.0 (comfortable), to 5.0 (extremely uncomfortable; Gagge *et al.*, 1967).

Ratings of perceived exertion (RPE) were assessed after the method of Borg (1962), for the whole body, legs and chest. Effort sensations were initiated from the question: "How hard does the exercise feel for your whole-body/chest/legs?". Subjects answered using the 15-point scale. Differential RPE scores were used, since Pandolf (1978) demonstrated that subjects perceive exertion according to the manner in which they experience the exercise stress. Thus, a subject with little cycling experience would be expected to perceive the legs as the site of greatest physiological strain.

Statistical analysis involved the use of multivariate analysis of variance, with Tukey's HSD post hoc procedure, and paired t-tests. For all analyses, alpha was set at the 0.05 level. Data, with the exceptions of descriptive statistics (standard deviations), are presented as means with standard errors of the mean.

3. Results and Discussion

3.1 Acclimation-induced changes in physiological function

The heat-acclimation protocol did not result in significant elevations in $\dot{V}O_{2peak}$ between either Days 0 and 6, or Days 0 and 19 (Table 4; $p > 0.05$). However, training adaptation did occur, with all but one subject showing an increase in peak power generation from Day 0 to Day 19, during the incremental exercise test conducted under temperate thermal conditions (Table 4; $p < 0.05$). This indicates that subjects increased their exercise efficiency, since peak power was elevated, while their $\dot{V}O_{2peak}$ was unchanged. The failure to increase $\dot{V}O_{2peak}$ is more a reflection of the pre-experimental training status of the population sample, than it is an index of the training stimulus provided by the acclimation protocol. That is, since these subjects were, on average, well trained before commencing the experiment (Table 2), the probability of an improvement in $\dot{V}O_{2peak}$ accompanying such an heat-acclimation regime, was limited.

During the three HSTs (Days 1, 8 and 22), physical work capacity in the heat was assessed. The total work completed during the first 90 minutes of the HST increased on each day: 513.1 ± 37.7 kJ; 538.5 ± 31.0 kJ; and 563.6 ± 34.2 kJ, respectively. The difference between Days 8 and 22 was significant ($p < 0.05$). The work performed during the incremental exercise stage at the end of the 90-minutes cycle period increased from Day 1 (57.8 ± 12.7 kJ) to Day 8 (83.8 ± 19.2 kJ), and then remained stable

from Day 8 to Day 22 (83.1 ± 16.9 kJ). The difference between days was only significant for the comparison between Days 1 and 22 ($p < 0.05$). When these components were summed, to determine the total work completed during each HST, it was found that the combined heat-acclimation protocol significantly elevated physical work capacity in the heat: 554.4 ± 48.3 kJ (Day 1), 610.3 ± 47.8 kJ (Day 8) and 646.7 ± 38.1 kJ (Day 22). Differences between Days 1 and 22, Days 8 and 22 were significant ($p < 0.05$). Thus, the heat-acclimation protocol increased the capacity of these subjects to perform work. However, this improvement was not apparent within the first 8 days of acclimation.

Table 4. Peak aerobic power and peak cycle power.

Subject	V _{O2peak} (L.min ⁻¹) Day 0	V _{O2peak} (L.min ⁻¹) Day 6	V _{O2peak} (L.min ⁻¹) Day 19	W _{peak} (watts) Day 0	W _{peak} (watts) Day 6	W _{peak} (watts) Day 19
S1	4.179	4.294	4.897	375	354	402
S2	6.694	6.337	6.489	546	489	555
S3	3.817	3.845	4.174	366	334	396
S4	4.549	4.792	4.527	423	426	432
S5	4.254	4.063	4.146	378	285	399
S6	3.332	3.337	2.887	270	267	279
S7	3.815	3.412	3.340	309	294	312
S8	-	-	-	330	327	330
Mean	4.377	4.297	4.351	374	347	388
S.D.	1.093	1.030	1.165	84	76	85

Abbreviations: V_{O2peak} = peak oxygen uptake (aerobic power) measured during an incremental semi-recumbent cycle protocol; W_{peak} = peak cycle power generated during this protocol.

3.2

3.3 Psychophysical indices

Thermal sensation (Figure 1) followed the typical response patterns observed during exercise in the heat, moving from 6.8 (slightly cool to neutral) during neutral rest, through to 11.7 (very hot to extremely hot) at the end of incremental exercise on Day 1. Pre-exposure thermal sensations were significantly lower on Days 8 and 22 ($p < 0.05$), with the standard response pattern again replicated on these days. Accordingly, the downward displacement of these curves following heat acclimation (Figure 1), is attributable to the offset in baseline thermal sensation prior to commencing the heat exposure, rather than to heat-acclimation induced changes occurring during the course of the HST.

Thermal discomfort increased linearly over time (Figure 2), commencing at 1.2 (comfortable to slightly uncomfortable) and increasing to 4.3 (very uncomfortable to extremely uncomfortable) on HST Day 1. On this index, there was no displacement of the pre-exposure baseline. However, each of the subsequent response curves was shifted downwards, relative to data obtained on the previous trial. Consequently, differences between Days 1 and 22 were significant during rest in the heat, and after 90 minutes of exercise in the heat ($p < 0.05$), but no other differences were significant ($p > 0.05$). Thus, heat acclimation resulted in reduced thermal discomfort, at the same relative exercise intensity, during subsequent heat exposure.

The changes in both thermal sensation and discomfort, accompanying heat acclimation, are believed to be primarily a function of reduced thermal strain experienced on HST conducted on Days 8 and 22. Heat acclimation results not only in a reduced T_{c} for a given heat and exercise loading (Greenleaf and Greenleaf, 1970; Sciaraffa *et al.*, 1980; Regan *et al.*, 1996), but may also lower the thermoneutral T_{c} (Cotter *et al.*, 1997). These T_{c} changes were similarly observed during the current cognitive-function tests days (Days 2 and 20; Table 5). Accordingly, the downward displacement of thermal sensation (Figure 1) is attributed to a lowering of the pre-exposure T_{c} , which was then carried through the experiment, while the displacement of thermal discomfort (Figure 2), is ascribed to a lower T_{c} during each HST following heat acclimation.

Ratings of perceived exertion also increased linearly over time during the first 90 minutes of exercise, and thereafter were sharply elevated in accordance with the incremental exercise to exhaustion (Figure 3). None of the between-trial comparisons in effort sense were significant for either the whole-body ratings, or for the fractionated ratings ($p > 0.05$).

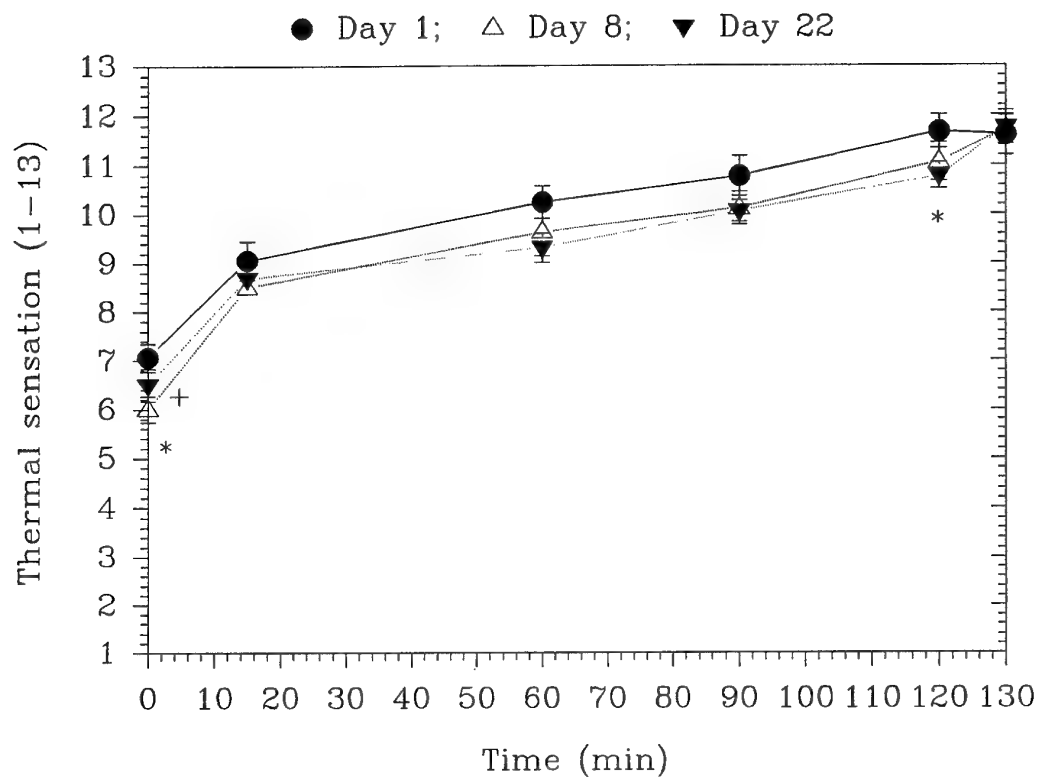


Figure 1. Thermal sensation during rest (0-20 minutes), steady-state cycling (20-120 minutes), and maximal incremental cycling (120-130 minutes) at an air temperature of 39.8°C (S.D. 0.5; relative humidity 59.2% S.D. 0.8). Symbols indicate that the difference between Days 1 and 8 (+), or Days 1 and 22 (*) was significant ($p < 0.05$).

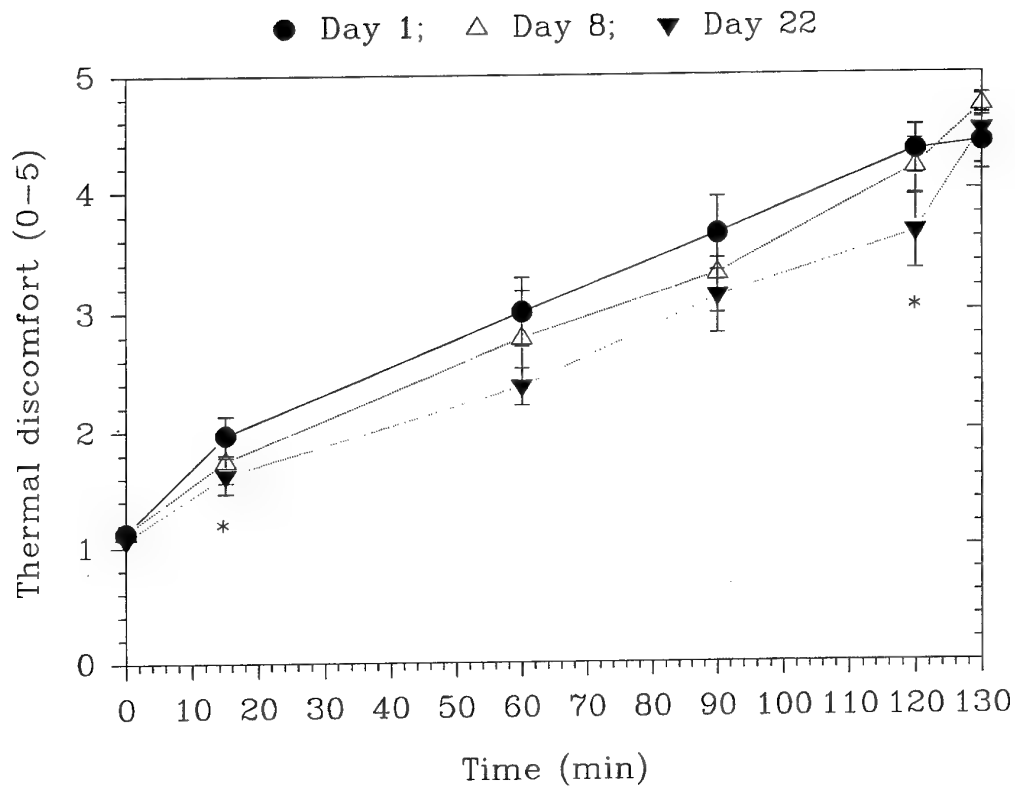


Figure 2. Thermal discomfort during rest (0-20 minutes), steady-state cycling (20-120 minutes), and maximal incremental cycling (120-130 minutes) at an air temperature of 39.8°C (S.D. 0.5; relative humidity 59.2% S.D. 0.8). Symbols indicate that the difference between Days 1 and 22 (*) was significant ($p < 0.05$).

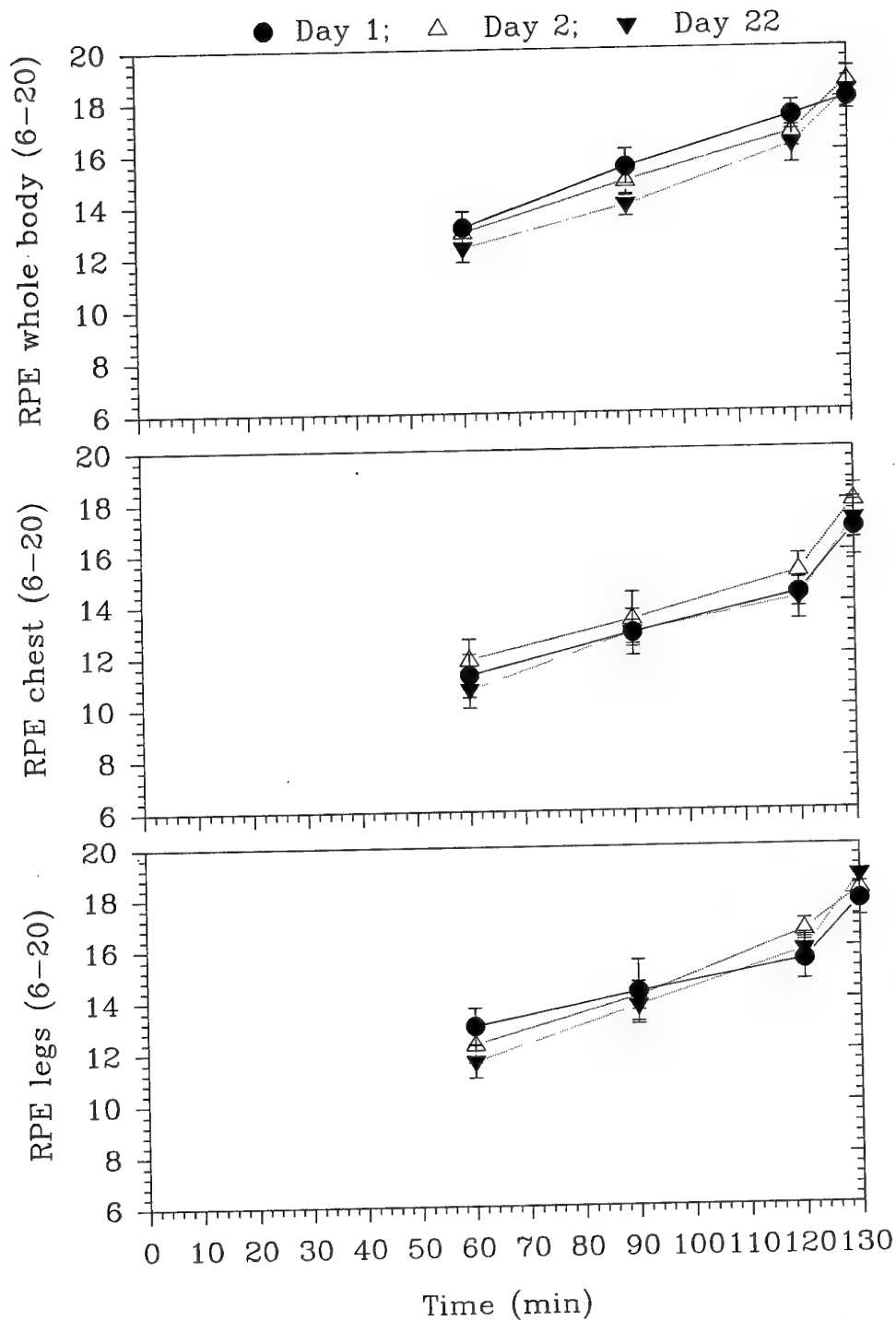


Figure 3. Ratings of perceived exertion during steady-state cycling (20-120 minutes) and maximal incremental cycling (120-130 minutes) at an air temperature of 39.8°C (S.D. 0.5; relative humidity 59.2% S.D. 0.8).

3.4 Cognitive function

Considerable human factors research has been undertaken in thermally stressful environments. However, not all such work has involved the quantification of thermal strain, or the application of suitable stresses upon the subjects. The current study sought to redress this situation. Cognitive-function tests were completed within the last 10 minutes of each 90 minutes acclimation exposure on Days 2 and 20. This protocol ensured that all subjects were exposed to a protracted elevation in T_c . During this testing, the following conditions applied:

- (i) T_a was 39.6°C (± 0.6 ; Day 2) and 39.6°C (± 0.1 ; Day 20);
- (ii) subjects were cycling at 21.1% (± 1.14 ; Day 2 and 20) of $V_{O2\text{peak}}$; and
- (iii) the mean work rate was 77.0 watts (± 2.2 ; Day 2) and 80 watts (± 2.6 ; Day 20).

Subjects were heavily stressed at this point, as reflected by their mean T_c (i.e. $(T_{re} + T_{ac})/2$) being 38.9°C ($\pm 0.1^{\circ}\text{C}$; Day 2) and 38.2°C ($\pm 0.3^{\circ}\text{C}$; Day 20). The other indices of strain are summarised in Table 5. Of particular note is the magnitude of the relative f_c (Day 1 and 20), its acclimation-induced reduction on Day 20, and the resultant mass losses on each test Day (1.55 and 2.23 kg, respectively).

Table 5. Summary of thermal strain at the time of cognitive-function testing.

Variable	Day 2	Day 20
auditory canal temperature ($^{\circ}\text{C}$)	38.7 (0.04)	38.2 (0.1)
rectal temperature ($^{\circ}\text{C}$)	39.1 (0.1)	38.3 (0.2)
mass loss (kg)	1.55 (0.1)	2.23 (0.2)
cardiac frequency (b.min ⁻¹)	155.8 (4.2)	135.8 (3.1)
maximum f_c (b.min ⁻¹)	186.0 (2.2) Day 0	178.8 (3.6) Day 19
percentage maximum f_c (%)	83	76

Notes: Data are means with standard errors of the means in parenthesis. Data were obtained from the heat-acclimation days during which cognitive function tests were performed (Days 2 and 20), and do not include responses occurring on heat stress Days 1, 8 and 22. f_c = cardiac frequency. Mass loss was corrected for fluid consumption at 30 and 60 minutes.

Spatial orientation (hand-identification task) was unaffected by heat exposure with all subjects achieving maximum scores during the third cognitive-function test (Day 2). This observation is consistent with that of Nunneley *et al.* (1982), and was interpreted as indicating that spatial orientation, as evaluated from this test, within the current experimental design, was unaffected by the combined stresses of exercise and thermal loading. Consequently, this function was not reassessed on Day 20 of the protocol.

Visual inattention (line-bisection task) was similarly unaffected by either unaccustomed heat exposure, or by heat exposure following 16 days of combined exercise and heat acclimation (Figure 4). The scores obtained from this test were mean percentage deviations from the true centre of all marked lines. Figure 4A shows that, on average, this deviation did not exceed 2% on any of the tests. Positive scores recorded when the right hand was used, are indicative of visual inattention. Such scores were observed on trials 2 (Day 1) and 4 (Day 20), though these trends were non-significant ($p > 0.05$). The difference between tests 2 and 3 was significant ($p < 0.05$), and is indicative of improved visual attention during the first cognitive-function test performed in the heat. However, each of these deviations from the zero axis is considered to be within the measurement error for this technique. Furthermore, there were no significant differences between the number of lines marked to either the right or left of the true line centre (Figure 4B). Accordingly, the results from this test imply that, under the current experimental conditions, visual attention appeared to be largely uninfluenced by heat strain

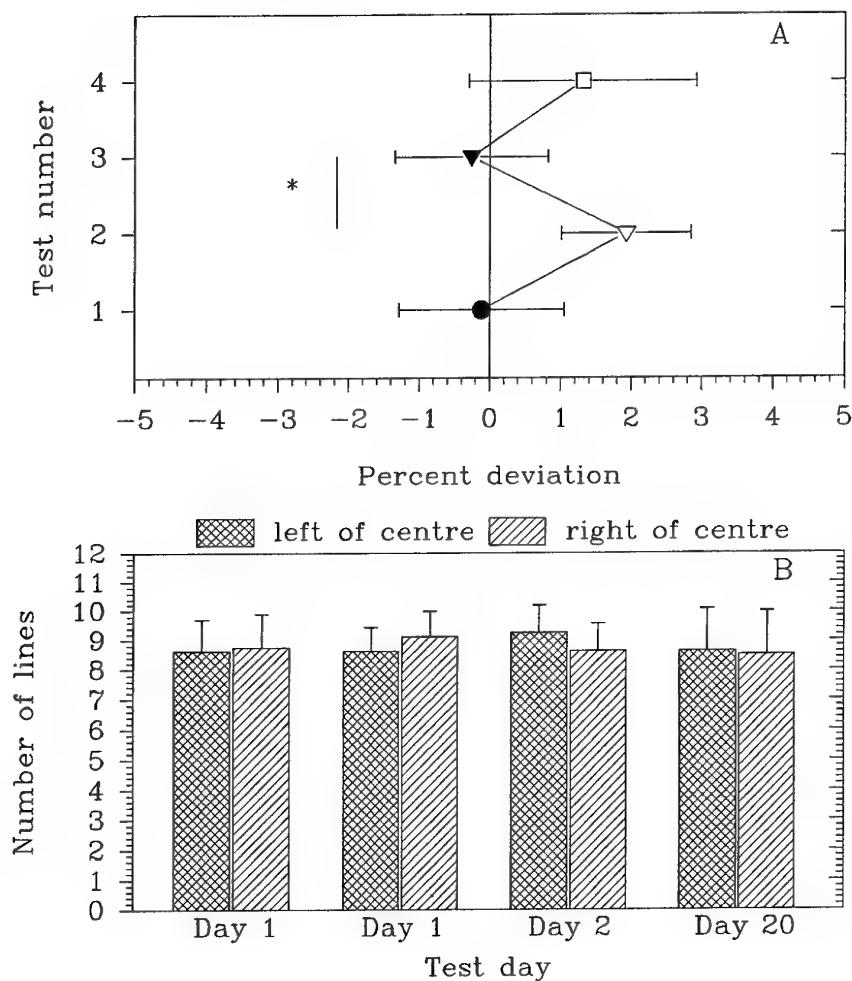


Figure 4. Visual inattention assessment, from a line-bisection task, after 80 minutes of steady-state cycling at an air temperature of 39.8°C (S.D. 0.5; relative humidity 59.2% S.D. 0.8). Panel A: percentage deviation from the true line centre. Panel B: the number of lines marked to the right or left of centre. The asterisk in Panel A indicates that the difference between tests two and three was significant ($p < 0.05$).

Temporal orientation (time-recall and time-estimation tasks) showed a slight, but non-significant ($p > 0.05$), interaction with thermal strain (Figure 5). Due to the strict regimentation of the procedures on Day 1 (HST), as demanded by the methods employed for determining body-fluid composition and controlling food and fluid intake, subjects had received numerous time cues which were not provided on test Days 2 and 20. Consequently, data from this day were not analysed. Date and day recall were always close to 100%. Neither the estimation of the duration of exercise, the time the cognitive-function tests were performed, nor the estimation of the duration of the cognitive-function test were affected by repeated heat exposure, with the results from Days 2 and 20 being dispersed about zero (Figure 5).

Real time was underestimated on Day 2 (Figure 5). On Day 20, the magnitude of this underestimation was reduced approximately four-fold. However, due to a 50-minutes underestimation by one subject, representing an error more than twice that of any other subject and 10 times greater than his error on Day 2, the difference between Days 2 and 20 was not significant ($p > 0.05$). When the Day-20 time estimation for this subject was excluded from the analysis, real time estimation was found to be significantly improved following 16 days of heat exposure. Taken collectively, these observations show that temporal orientation is not significantly affected by either unfamiliar heat strain, or heat strain following heat acclimation.

Sustained attention or vigilance (letter-cancellation task) was not influenced by thermal strain (Figure 6). Scoring for this test was based upon errors and omissions. Figure 6A shows the percentage of letter cancellations attempted (relative to the total number of letters: 416), and the number of missed cancellations within 60 s (relative to the total number of letters cancelled). In the former instance, it is clear that, while the scores had apparently reached a plateau from test 2 onwards, subjects had not yet completed learning for this task. That is, the number of cancellations attempted increased significantly between trials 1 and 2 (both on Day 1), and between trials 2 (Day 1) and 3 (Day 2). However, learning effects were not apparent within the other indices, and there were no significant differences between either the percentage of missed letters (Figure 6A), or the percentage of correct cancellations (Figure 6B), across any of the four tests. These data are interpreted as demonstrating that unfamiliar heat exposure neither reduces the ability for focussing on a given task, nor induces attentional disturbance.

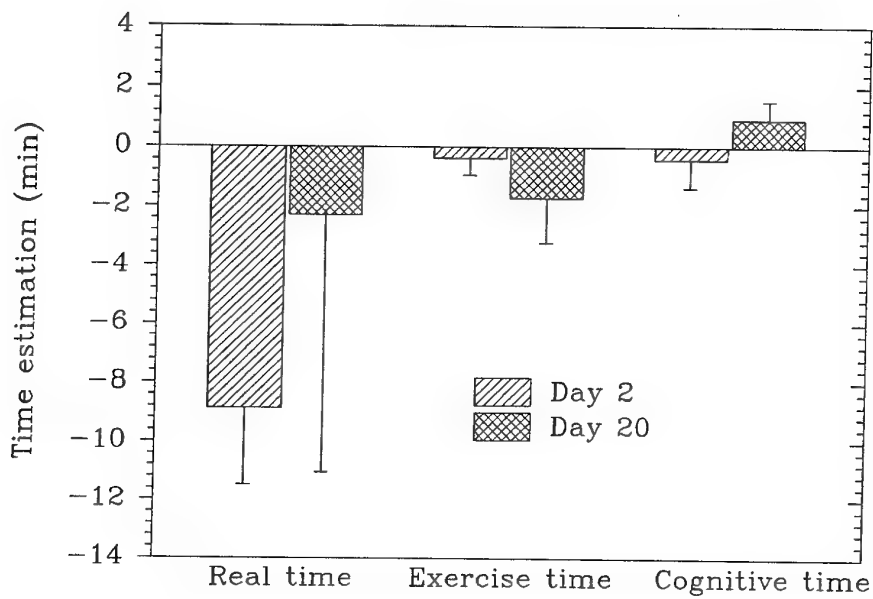


Figure 5. Time estimation after 80 minutes of steady-state cycling at an air temperature of 39.8°C (S.D. 0.5; relative humidity 59.2% S.D. 0.8). Estimated times were: the actual (real) time, duration of exercise, and the duration of the cognitive-function test battery.

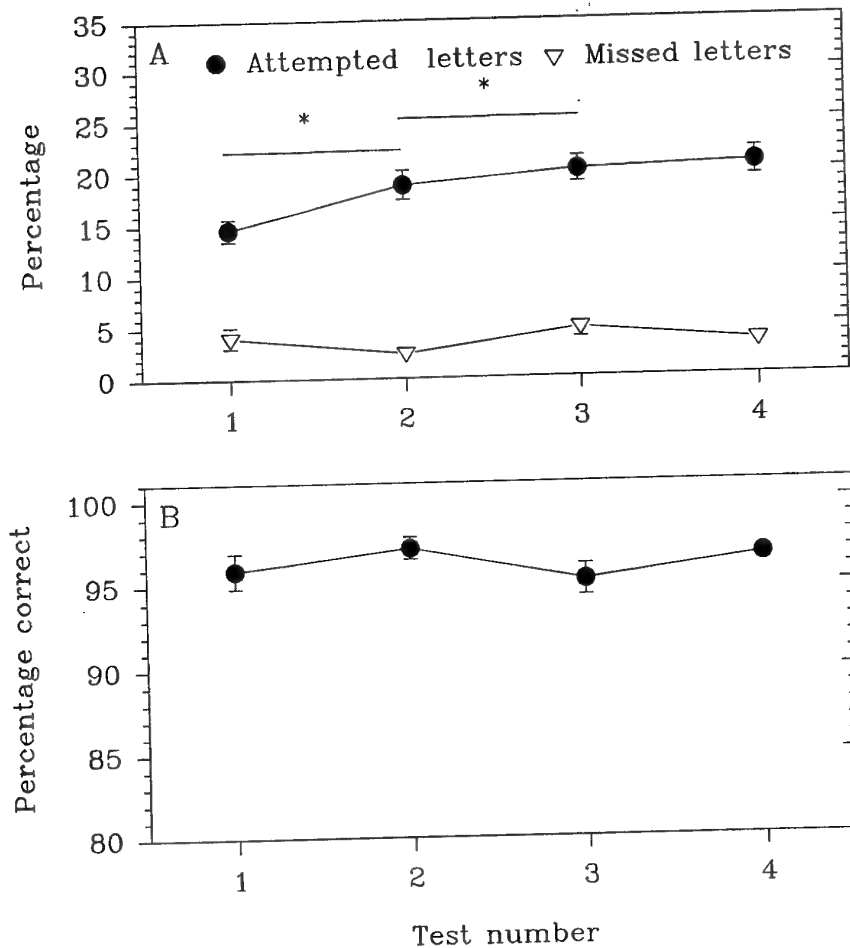


Figure 6. Sustained attention (vigilance) after 80 minutes of steady-state cycling at an air temperature of 39.8°C (S.D. 0.5; relative humidity 59.2% S.D. 0.8). Panel A: the percentage of attempted and missed letter cancellations. Panel B: the percentage of correct letter cancellations. The bars with an asterisk in Panel A indicate that the difference between two tests was significant ($p < 0.05$).

Previously, Mackworth (1950) and Benor and Shvartz (1971) had reported impaired vigilance during heat exposure. In the latter instance, auditory vigilance was evaluated while subjects walked at various T_a while wearing a water-perfusion suit. Nevertheless, earlier observations by Poulton and Kerslake (1965), concerning the early phase of body heating, and Wilkinson *et al.* (1964), on more sustained thermal strain, found that cognitive function was elevated following heat exposure.

Therefore, it may be concluded, on the basis of the current cognitive-function tests, that high levels of thermal strain, combined with exercise capable of inducing a f_c greater than 75% of maximal f_c do not impair visual attentional, temporal or spatial orientation, or visual perception. While the tests chosen to assess these cognitive functions were selected to evaluate the general hypothesis that heat strain affects cognitive function, it might be argued that other tests may be more appropriate for use in more applied settings. For instance, the current test results, while permitting evaluation of generalised hypotheses related to cognitive function, may not permit the derivation of group-specific or task-specific outcomes. However, the limitation of using more complex real tasks, or real-task simulations, is that the results may become difficult to interpret. That is, due to the complexity of some job-specific tasks, it may only become possible to show that task performance was affected by the intervention, and impossible to identify the cause of the effect. For example, because many job-specific tasks involve a number of separate cognitive functions, a change in performance, in the absence of function-specific tests, cannot be ascribed to changes in any single cognitive function. Consequently, such information will have limited general applicability to other situations, and will be of little benefit to the establishment of preventative measures. However, while the current data show that, on function-specific tests, separate cognitive functions appear to be neither impaired by heat strain nor restored following heat acclimation, these data tell us nothing about the impact of heat strain upon more complex tasks. That is, it may be that only within the framework of the more complex task, where there is the simultaneous involvement of multiple cognitive functions, that performance becomes affected by thermal strain. The results of Hancock (1982) support this possibility, indicating that the effects of thermal strain may be apparent earlier during the performance of more complex tasks.

The discrepancy between the current results, and those of some, but not all, previous investigators is not easy to reconcile. However, there are a number of experimental factors which may account for such differences. Firstly, the means by which thermal stress was applied to the subjects must be considered. In the current design, heat was provided both endogenously (metabolic heat) and exogenously (climate chamber). However, numerous studies have used exogenous heat stress on its own. Perhaps the most extreme case comes from the work of Fox *et al.* (1967), where subjects, wearing vapour-barrier suits, were passively heated using hot air passing through the suit, to elevate T_c to 39°C. In similar studies in our laboratory, we have found this form of passive heat stress to be physiologically demanding, quite over-powering, and very uncomfortable. Therefore, we do not find it surprising that cognitive function

decreased when using this design. Thus, it may be concluded that resultant changes in cognitive function may be influenced by the method of heat application.

Secondly, much of the early psychological research did not account adequately for the impact of heat upon T_c . For instance, numerous studies have only reported changes in T_a , or various forms of psychometric or effective thermal scales, and have implicitly assumed that changes in cognitive function were simply related to such conditions, rather than to the impact of the environment upon body temperatures. Since the capacity to tolerate heat is widely variable between people, and since cognitive function is less likely to be affected by T_a than it is by its expression at the body core (T_c), then it is more relevant to relate cognitive function to T_c . This discrepancy is exemplified by the thermal tolerance curves developed by Wing (1965), where performance was related to both exposure duration, and effective temperature⁴. While not exclusive of T_c changes, this index may be unrelated to physiological strain. These tolerance curves led to the development of the notion that mental performance began to deteriorate before physiological tolerance limits were reached⁵ (Hancock, 1981). However, Hancock (1981) suggested that mental performance is only impaired when physiological function is about to fail. That is, when the ability to maintain thermal homeostasis is lost, so too is the capacity to perform cognitive tasks without impediment. While the current subjects were heavily stressed, they were not dysthermic, nor did they suffer impaired cognitive function. Consequently, while not testing Hancock's (1981) hypothesis, these data are consistent with that position.

Thirdly, Gopinathan *et al.* (1988) demonstrated that hydration status acts as a covariate with thermal strain upon cognitive function. They found that a 2% dehydration resulted in impaired mental function. With very few exceptions (see: Sharma *et al.*, 1986), hydration state has frequently not been considered in experiments investigating heat and cognitive function. However, to prevent progressive dehydration in the current investigation, subjects commenced each HST, each heat-acclimation exposure, and both cognitive-function trials in a rigidly controlled, euhydrated state. The current sweat losses represented 2.0% (Day 2) and 2.9% (Day 20) mass reductions, of which 400 ml (0.5% of total mass) was replaced before the cognitive-function tests were performed. It is possible that previous research showing reduced cognitive function,

⁴ There are two families of thermal stress indices: effective temperature (or sensation) scales and rational scales, which are based upon the use of the heat balance equation, and the relation between the heat exchange components and physiological strain. The Effective Temperature scale was introduced by Houghten and Yagloglou (1923) to define various combinations of dry-bulb temperature, air motion and relative humidity which would provide the same thermal sensation to occupants of enclosed spaces. This scale has limited physiological application since: it was developed using transient thermal sensations, non-standard clothing, sedentary subjects (later modified); environments that were close or near to the comfort zone; it overemphasises the effects of dry-bulb temperature at the upper end of the scale; and it fails to adequately take into account the effects of air velocity under hot-humid conditions.

⁵ This position was accepted by the National Institute for Occupational Safety and Health (U.S.A.) in 1972.

particularly under protracted exposures, may reflect this interaction between heat loading and hydration state.

Finally, differences in the assessment of cognitive function between various projects could account for some of the discrepancies between observations. For instance, cognitive function has been assessed using a wide range of tasks, drawn from various psychophysical domains, some with uncertain validity, and applied with varying degrees of between-project consistency. To illustrate this, both the current project and Nunneley *et al.* (1982) used a simple hand-identification task on a manikin to evaluate spatial orientation. However, Ramsey *et al.* (1975) and Fine *et al.* (1958) both assessed conceptual function differently. But Ramsey *et al.* (1975) used a mental multiplication task, while Fine *et al.* (1958) used anagram solving. It is possible that the range of complexities of the cognitive, perceptual and attention tasks used in early investigations may account for the apparent thermal effects observed by different investigators. For example, Carlson (1961) varied task complexity in hot and neutral environments, finding that performance was only reduced in the hot environment with the high complexity task. Similarly, Epstein *et al.* (1980) used three different sizes of aiming targets in three different environments (cool, moderately warm and hot). Aiming accuracy using the largest target was not affected by environmental temperature. However, as the target size was reduced and environmental temperature was elevated, performance was compromised. In a similar manner, differences in the duration of the task may also account for differences between investigations (Wilkinson, 1969). Furthermore, we must consider the sensitivity of the tasks employed. A number of cognitive-function tests have arisen from research into altered brain function accompanying various pathological states (*e.g.* Parkinson's disease: Talland and Schwab, 1964; cerebral disease: Benton *et al.*, 1964) or neurological impairments (*e.g.* brain damage: Schenkenberg *et al.*, 1980, and Ratcliffe, 1979). It is possible that, within these states, where brain function is more severely affected, such tests may have adequate sensitivity. However, it is quite possible that heat-induced cognitive impairment is a relatively mild change, and the tests do not have the sensitivity required to measure such subtle changes.

4. Conclusions

This investigation had three main purposes: (i) evaluating the effects of short- and long-term exercise and heat acclimation upon the ability to perform physical work; (ii) to revisit the hypothesis that unaccustomed thermal strain is a hindrance to normal cognitive function; and (iii) to test the thesis that, following exercise and heat acclimation, cognitive function will return towards normality.

The current observations demonstrate that heat acclimation improves the capacity to perform physical work in the heat. This not only agrees with the literature (Greenleaf

and Greenleaf, 1970; Sciaraffa *et al.*, 1980), but extends our demonstration that isothermal heat acclimation reduces physiological strain during acute heat exposure (Regan *et al.*, 1996). However, this improvement in physical work capacity was not apparent following the first eight days of acclimation. Since this acclimation duration would typify that used for most military applications, it may be concluded that, for the purposes of improving the capacity of personnel to perform work in the heat, more protracted heat-acclimation programmes may be required.

Neither unaccustomed, nor habitual, heat strain appeared to induce attentional disturbances, temporal or spatial disorientation, or altered visual perception, as quantified using the current cognitive-function tests within this experimental design. While it is uncertain why such trends were not apparent, it may be concluded that such observations were not due to the application of an inadequate thermal loading on the subjects, since T_a was 39.6°C, mean T_c at the time of testing was 38.9°C (Day 2) and 38.2°C (Day 20), the relative f_c exceeded 75% of maximal f_c , and mass losses exceeded 1.5 kg (2.0% body mass; Day 2) and 2.2 kg (2.9% body mass; Day 20).

5. Recommendations

Given the equivocal nature of the research evidence, it is recommended that further investigations be undertaken to specifically address the effects of thermal strain upon cognitive performance. Firstly, it is recommended that, in consultation with psychologists experienced in cognitive-function assessment, a thorough reassessment of the impact of acute thermal strain upon simple cognitive function be investigated. Such research should be undertaken within both controlled-hyperthermic and uncontrolled-hyperthermic conditions, during both transient and extended exposures, in iso-hydration and dehydration states, and with and without clothing. To ensure adequate coverage of psychophysical domains, it is recommended that a test battery be constructed, from valid and reliable tests, to evaluate perceptual function (visual and auditory), memory function, conceptual function (verbal and arithmetic), orientation (temporal and spatial), and vigilance.

Secondly, in consultation with psychologists, task and function analyses are undertaken, with the ADF, to determine the broad duties in which both thermal strain and cognitive function tasks are likely to interact, to identify and categorise the types of skills required by these duties, and to group these skills into their corresponding psychophysical domains (e.g. Table 6). From this classification, it should be possible to undertake field observations to identify those operations which are more susceptible to heat strain. Some cognitive functions may be more affected than others. For instance, if it is shown that, for the duty of interest, tracking tasks are never performed under thermal stress conditions, then the inclusion of such a test will be of little relevance to either the experimental subjects or the perceived outcomes of the research.

Thirdly, it is recommended, on the basis of these observations, that job-specific tests (complex cognitive-function tasks), or task simulations, be developed, and the impact of thermal loading upon these tasks be assessed. Such tests should be performed using 'real environment' simulations, including thermal, auditory and visual distractions.

Table 6. Hypothetical breakdown of the psychophysical domains and job tasks which may be relevant to weapons operators (from Patterson et al, 1997).

Domain	Job tasks
Perceptual domain	visual interpretation
	auditory cue detection
	tactile recognition of controls
Cognitive domain	sustained attention to cues
	decision making
	response selection
Motor domain	response activation
	reaction time

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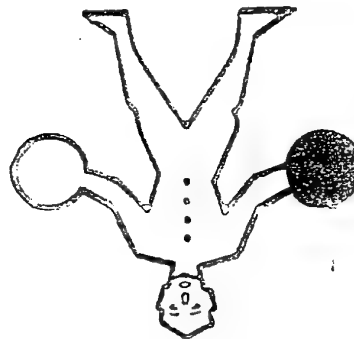
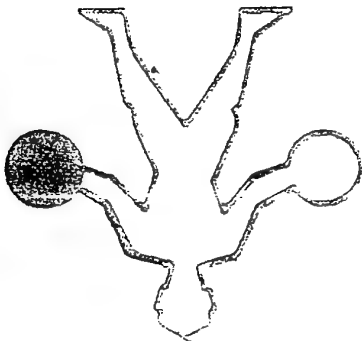
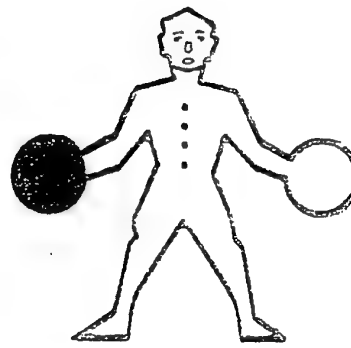
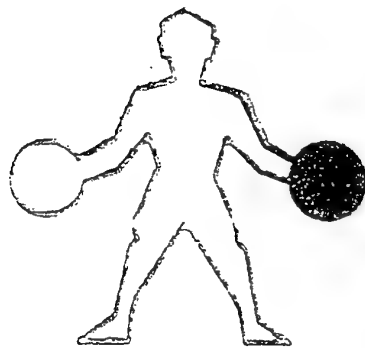
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Appendix 1

Written instructions and sample practice sheets for the cognitive-function tests.

(i) Spatial orientation task

You will be presented with a person (manikin) holding a black (closed) circle in one hand, and an open (empty) circle in the other. You are required to determine which of the person's hands holds the black circle. Answer: 'left' or 'right' within one second of being shown the picture. The person may be facing you, or facing away from you, and may be positioned upright on the page, inverted or sideways along the page. Thus, the person has eight possible positions: upright facing forwards; upright facing backwards; upside down facing forwards; upside down facing backwards; sideways with head on left side and facing forwards; sideways with head on right side and facing forwards; sideways with head on left side and facing backwards; and sideways with head on right side and facing backwards. Examples are given below, with all people possessing the closed circle in their right hands.



(ii) Letter cancellation task:

This task involves crossing out letters. You will be presented with a sheet of paper containing 416 letters (16 rows of 26 lower- and upper-case letters). Your task is to mark all upper-case letters and all lower-case letters following a double space (excluding margins) using a single line. However, upper-case letters which follow a double space are to be marked with a cross (examples are shown below). You have 60 seconds to complete the page.

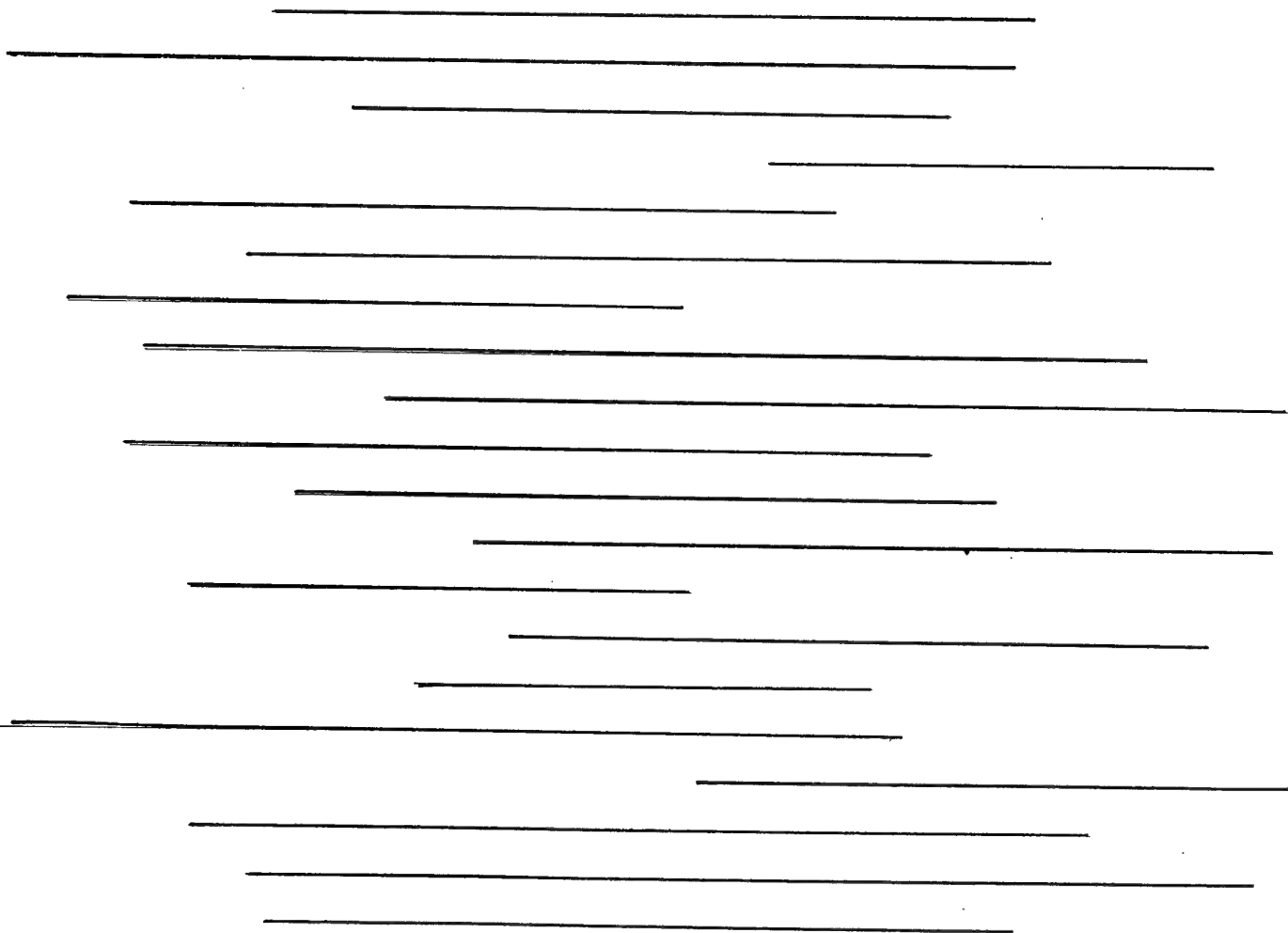
yGsWp SkXeVm ndfkypTl aPJzbefk dLiKosnfd
 tadPwe Qr sdAjpMljXdnUb sYVv feyLij zKxvm
 vdUfQg sWopTwnc VbEvzAxN sjheXtyf Poujnh
 vxsDgoj meQkgh AdbYcAvgZetXs opLnhHe fYl

(iii) Temporal orientation task:

You will be questioned concerning the passage of time during the course of the trial. Five measures of time will be used: today's date, the name of the day, the current time, time since you commenced exercising, and the time since the cognitive-function tests commenced.

(iv) Line bisection task:

You will be presented with 20 lines of different lengths, some of which cross the mid-line of the page. Your task is to cut each of the straight lines in half, by placing a small mark through each line as close as possible to its centre. Use your right hand, and keep the left hand off the table. Do not make more than one mark on any line. Mark each of the lines in sequence, and without skipping any lines. The task is finished when you have completed the full page.



Appendix 2

Written instructions and rating scales for the psychophysical indices.

(i) 15-point Borg scale

During the exercise period, we want you to pay close attention to how hard you feel you are working. This feeling should indicate the total amount of exhaustion and fatigue that you are sensing, combining all possible sensations of physical stress, effort and fatigue (no matter what their source). Do not concern yourself with any one factor, such as leg pain, shortness of breath or exercise intensity, but try to concentrate on your total, inner feeling of exertion. Do not underestimate or overestimate, just be as accurate as you can with your responses.

We will ask you: "How hard does the exercise feel?".

We will also ask you to rate this sensation for your whole-body, and then separately for your chest and your legs.

15-POINT BORG SCALE

- 6
- 7 Very, very light
- 8
- 9 Very light
- 10
- 11 Fairly light
- 12
- 13 Somewhat hard
- 14
- 15 Hard
- 16
- 17 Very hard
- 18
- 19 Very, very hard
- 20

(ii) 5-point thermal discomfort scale

During the test we want you to describe how uncomfortable you feel with the changes in your body's temperature. That is, we want you to rate your thermal discomfort. Do not concern yourself with any one area, such as your hands or feet, but try instead to concentrate on total body discomfort.

The thermal discomfort scale has numbers ranging from 1.0 (comfortable), to 5.0 (extremely uncomfortable).

We will ask you to give us a number that best represents your whole-body thermal discomfort at that moment.

We will ask: "How comfortable do you feel with the temperature of your body?".

THE 5-POINT THERMAL DISCOMFORT SCALE

- 1.0 Comfortable
- 1.5
- 2.0 Slightly uncomfortable
- 2.5
- 3.0 Uncomfortable
- 3.5
- 4.0 Very uncomfortable
- 4.5
- 5.0 Extremely uncomfortable

(iii) 13-point thermal sensation scale

During the test we want you to describe how your body temperature feels. That is, we want you to rate your thermal sensation. Do not concern yourself with any one area, such as your hands or feet, but try instead to concentrate on your total body temperature sensation.

The thermal sensation scale has numbers ranging from 1 (unbearably cold), to 7 (a neutral sensation), and finally to 13 (unbearably hot).

We will ask you to give us a number that best represents your whole-body thermal sensation at that moment.

We will ask: "How does the temperature of your body feel?"

13-POINT THERMAL SENSATION SCALE

- 1 Unbearably cold
- 2 Extremely cold
- 3 Very cold
- 4 Cold
- 5 Cool
- 6 Slightly cool
- 7 Neutral
- 8 Slightly warm
- 9 Warm
- 10 Hot
- 11 Very hot
- 12 Extremely hot
- 13 Unbearably hot

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Mark J. Patterson, Nigel A.S. Taylor and Denys Amos

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